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Methodology for Determining Optimal Tank Cannon Barrel Centerline Shape

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Methodology for Determining Optimal Tank Cannon Barrel Centerline Shape

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Abstract

This study describes the methodology for determining optimal gun tube centerline shape. It starts with describing system accuracy and then shows how different gun tube centerline shapes affect accuracy performance. The results show that the shape that imparts the smallest transverse disturbance has the best accuracy performance.

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1. Introduction

One of the largest influences on jump error is the centerline of the tank gun tube, therefore the U.S. Army is interested in reducing the variability in gun tube centerline shapes. Once this approach is adopted, there exists the question of what is the most optimal shape.

The U.S. Army uses a single "fleet zero" (also called surrogate zero or the computer correction factor [CCF]*) for each ammunition type. This translates loosely into average jump for a given ammunition type, where jump is defined as the difference between the aim point and impact point of a projectile. Inherent in this strategy is fixed (known or identifiable) system errors. The first error is related to projectile jump being a function of temperature. Because the CCF is averaged over a range of temperatures, the mean jump for a particular group of rounds at a given temperature will likely differ from the CCF. A second fixed error is related to the centerline of the gun tube. The CCF is derived from the average shape; therefore, any individual gun tube shape, unless it has the average shape, will have jump that differs from the system centerline average. The object of this report is to identify the optimal shape that will minimize this second fixed error using U.S. Army Research Laboratory's (ARL's) gun codes.

The optimal shape is determined by assessing variability in jump that results from overall shape, manufacturing variability in the shape, and centerline defects. This report details the methodology for the M256 gun system and shows an example shape.

2. System Accuracy

System accuracy is derived from projectile jump. Jump is defined as the vector from the intended point of impact (correcting for gravity drop) to the actual point of impact on the target see Figure 1a. Figure 1b displays two other aspects of a single occasion static firing that are important; one is the standard deviation of the impacts (defined as target impact dispersion [TID]), and the second is the average jump or center of impact (COI).

* For brevity, "fleet zero" will be referred to as the CCF in this report.

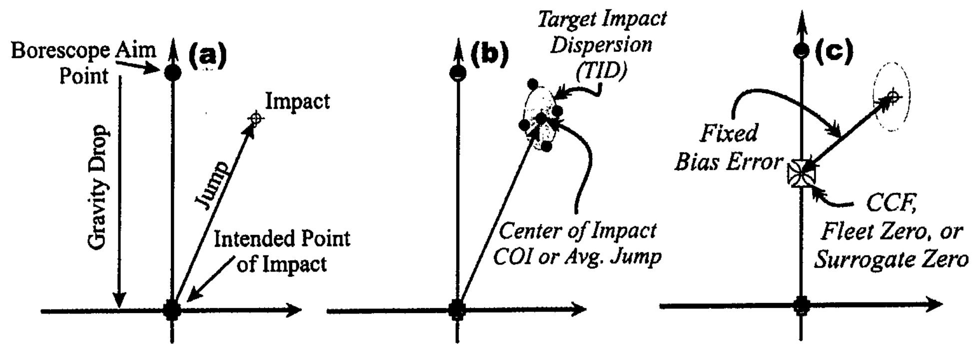

Figure 1. Jump definitions.

The Abrams tank fleet uses a CCF (fleet zero or surrogate zero) in its aiming procedure (fire control) to compensate for the average COI shift (averaged over a large number of barrels) for each round type (see Figure 1c). Because most barrels shoot slightly different than the average, there will be a difference between the COI for a given barrel on a given occasion and the CCF; this difference is called the fixed bias error, as shown Figure 1c.

Although occasion-to-occasion (occ-occ) error can be defined for a given tube based upon the spread in fixed bias errors over many occasions (as indicated in the leftmost illustration of Figure 2) when one value is quoted for this quantity, this value is usually taken to be the standard deviation of fixed bias errors over a large sampling of tubes and occasions, as implied by the rightmost picture in Figure 2.

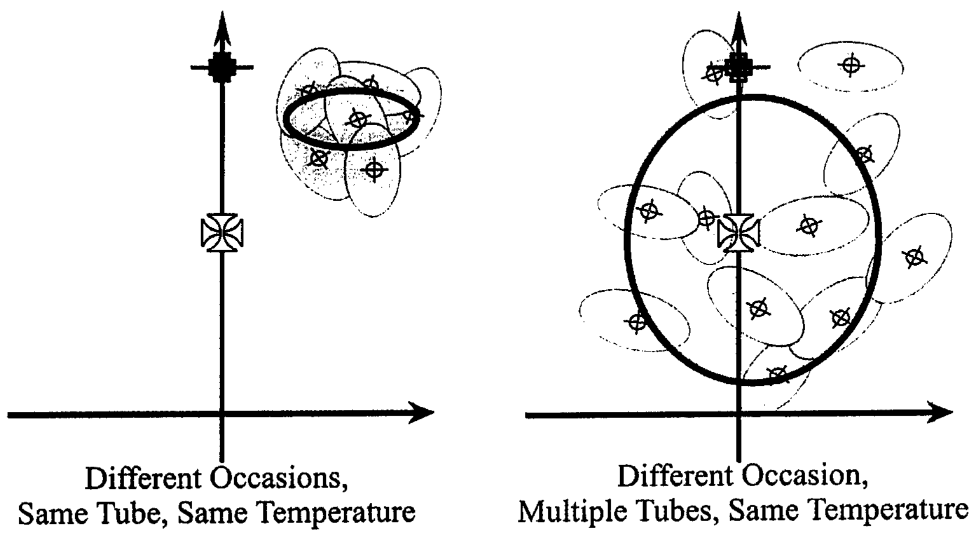

Figure 2. Occ-occ error from multiple occasions and multiple tubes.

Occ-occ error comes mainly from three sources: gun tube centerline effects, temperature jump effects, and miscellaneous effects. Figure 2 illustrates the centerline effects, or multiple gun tube effects, within the occ-occ error budget. Similarly, Figure 3 portrays the temperature-dependent part of occ-occ error. That is, the leftmost sketch represents the spread in shot impacts from firing the same tube at different temperature occasions, while the rightmost sketch depicts the same circumstances from multiple tubes. The gross shift in the COI groupings with change in temperature is not due to change in gravity drop with propellant temperature;* rather, it is due to jump differences caused by different dynamic interactions between the projectile (whose in-bore velocity is propellant-temperature dependent) and the tube centerline/gun system.

The third factor in occ-occ is miscellaneous error results from a combination of temperature-induced changes in the clearances of different parts of the gun system, small errors in aiming, and any other nonquantifiable sources of error. When compared to the centerline and temperature jump effects, the miscellaneous contribution is considered to account for only a small portion of the total occ-occ error. For simplicity, it can be assumed that the entire error budget is composed of just the two primary effects, viz., temperature jump effects (~50%) and tube centerline effects (~50%).

Because tube-to-tube variation is a substantial portion of occ-occ error, it stands to reason that standardizing the shape should reduce occ-occ error. This does not mean that all shapes are created equal. This report shows how to approach identifying the optimal gun tube shape through minimizing jump variability.

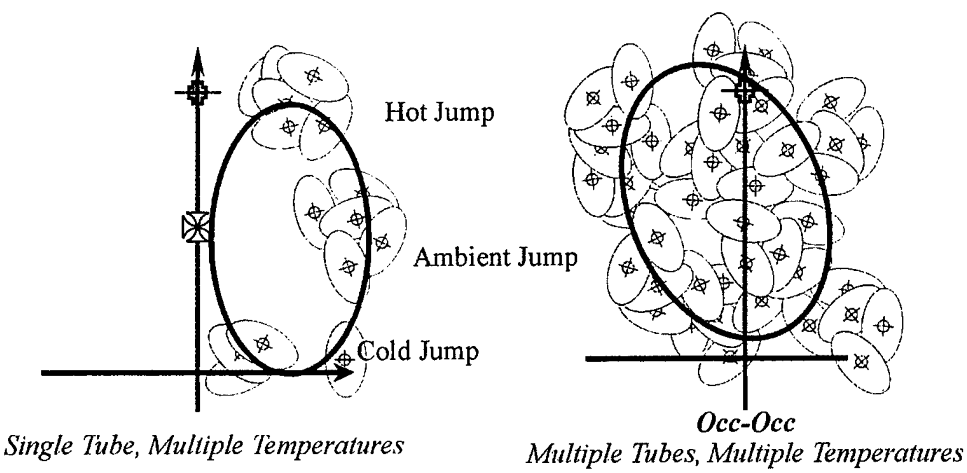

Figure 3. Occ-occ error from multiple temperatures, multiple tubes, and multiple occasions.

* The change in gravity drop with propellant temperature is accounted for in the fire control solution.

3. Approach

To find the optimal gun tube shape, projectile jump variability is used to show sensitivity to different types of shapes. Examples of the types of gun tube shapes that are used in the study are shown in Figures 4–6. Only variation in vertical centerline is analyzed. The tubes are shown with the forcing cone of each tube aligned. When the tubes are used in the simulations, the muzzle is aimed at the target in the same manner as the real system using a borescope.

The magnitudes of the shapes chosen are based on the difference of the angle at the muzzle of the tube and the origin of shot (forcing cone).* For the single bend tubes, this angle was varied between 1.8 mrad and -2.7 mrad for the tubes with the bends starting at 80 in from the rear face of the tube (RFT) and from 0.9 mrad to -1.35 mrad for the tubes with the bends starting at 150 in from the RFT. The magnitudes of these angles are representative of tank cannon tubes that have been made. For the multiple bend tubes, the muzzle angle varied between -1.5 mrad and 1.5 mrad. In terms of vertical displacement between the forcing cone and the muzzle, the tube shapes with two bends are the largest.

4. Numerical Simulation of Tank Gun Firing

Typically, three-dimensional (3-D) models of the M256 120-mm tank cannon launching saboted kinetic energy (KE) projectiles involve a mesh density on the order of 50,000–100,000 elements [1–6]. Material models used in these simulations include linear elastic, linear elastic-plastic, and a variety of materials for plastic obturators, springs, and other attributes. A special version of the hydrocode DYNA3D [7] was created in-house to capture important details involving the highly anisotropic nature of the composite materials used in modern sabots. Sliding interfaces are included to permit the gun to recoil realistically in the cradle, permit relative motion of the projectile with respect to the gun tube, and correctly define relative motion among the fully segmented sabot petals. The gun bore and chamber are appropriately pressurized, following typical interior ballistic pressurization rates and magnitudes as determined from the second edition of the Internal Ballistics High Velocity Gun 2 (IBHVG2) [8] ballistic models.

* The shot origin/muzzle angle difference will be denoted as the muzzle angle for the remainder of this report.

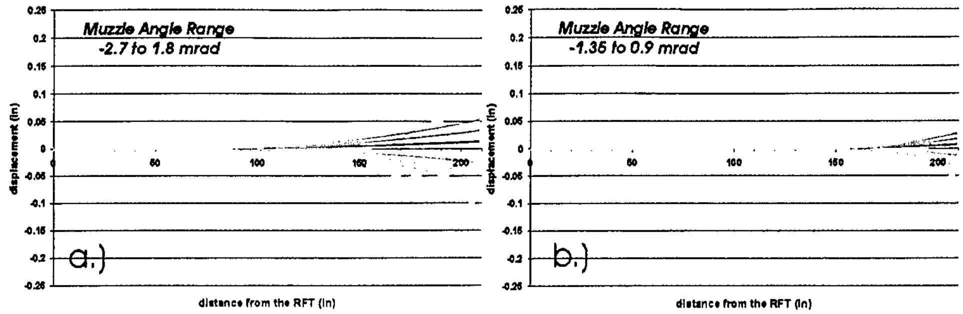

Figure 4. Single bend tube shapes.

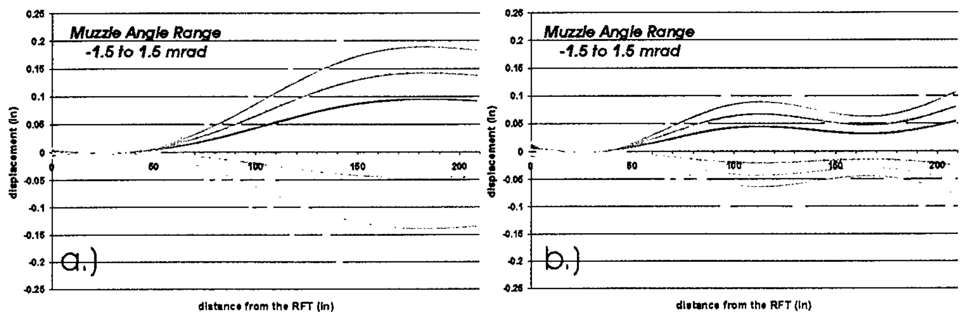

Figure 5. Tube shapes with two and three bends.

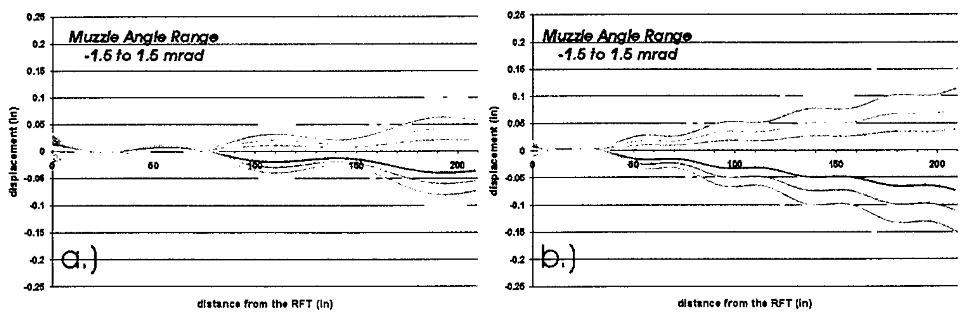

Figure 6. Tubes with five and ten bends.

5. Performance Predictions

A primary use of gun dynamics simulation is to predict shot-exit conditions (i.e., the average transverse velocity component of the projectile and the average angular rate of the projectile around its center of gravity [CG]). The definition of these quantities is given in Figure 7. Modeling the small clearances between the projectile bourrelets and the inner diameter of the gun tube, as well as bourrelet deformation under launch and balloting loads, allows the projectile to move (somewhat) independently of the tube.

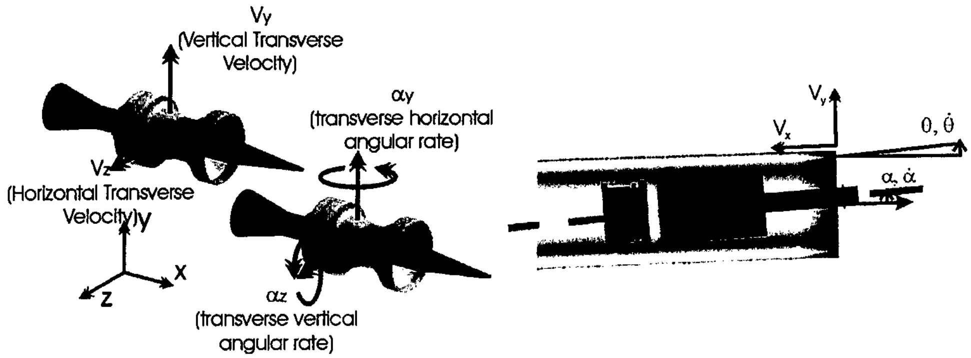

Figure 7. Definition of a projectile's rates and motion relative to the bore.

The influence of angular rates and transverse velocity at the muzzle on the projectile's trajectory to the target can be assessed through the traditional analysis of projectile jump [9, 10]. Two of the jump vector components that are predicted by the in-bore dynamics of the projectile are total CG jump and aerodynamic jump (AJ). Total CG jump is a combination of CG jump, crossing velocity (CV), and muzzle pointing angle (MP). Total CG jump is directly related to transverse velocity of the projectile's CG at muzzle exit. Aerodynamic jump is directly related to the initial angular rate at muzzle exit. Gun/projectile dynamic simulations (hydrocode) are used to predict the transverse angular rates and transverse velocities of the projectile at muzzle exit as well as to provide the entire dynamic path during the in-bore launch. For a more complete description of the projectile jump model see references [9, 10].

6. Results

To determine the optimal centerline shape, jump variability for a generic round is compared with the number of turns a projectile makes during launch, for comparable muzzle angles.

For each gun tube in this study, a series of simulations was accomplished. Each series of simulations represents a range of initial conditions and allows the jump variability to be calculated, which characterizes the tube shape's performance. Figure 8 shows projectile jump at the muzzle exit for all of the groups used for the analysis (400 simulations). The figure shows that the largest jump is in the vertical plane. This is reasonable because the perturbations in the tube shapes were in the vertical plane. The spread in the horizontal plane is due to the dispersion of the system (variation in launch conditions).

The primary conclusion from Figure 8 is that as the complexity of the path increases (i.e., the number of direction changes that a projectile is forced to navigate), the jump variability increases.

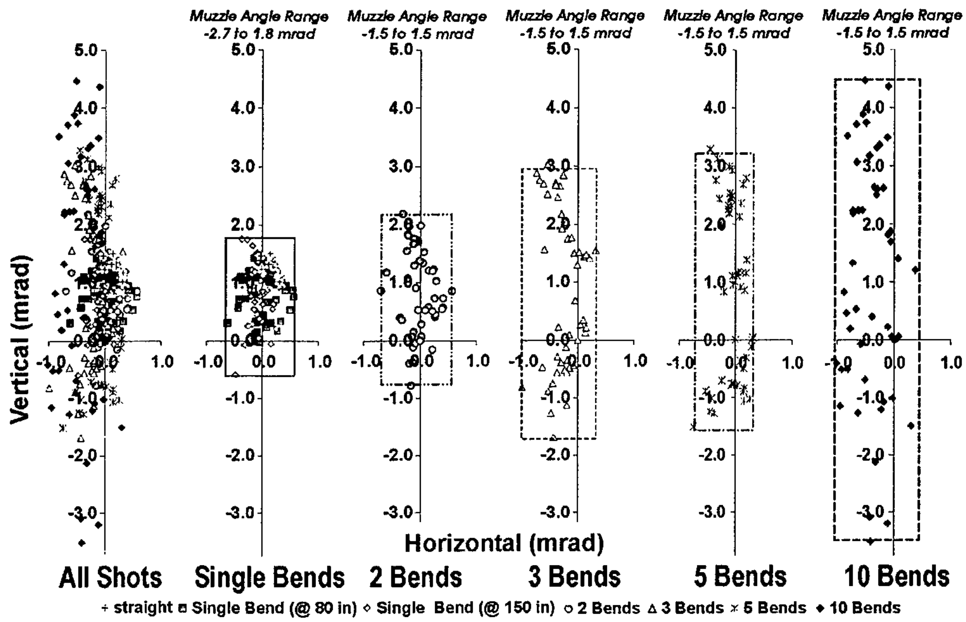

Figure 8. Muzzle jump of all configurations.

Figure 9 shows the vertical jump plotted against the muzzle angle. What is seen in this figure is that as the magnitude of the bends decreases, the magnitude of the jump variability also decreases. Based on the patterns revealed in the figures, it can be said that there is a correlation between jump variability and the number of bends as well as between jump variability and the magnitude of the bends. This implies that the jump variability is related to transverse energy imparted to the projectile and that smooth, relatively straight tubes are more optimal than tubes with multiple bends.

What remains to be shown is whether a single bend can provide an optimal shape. Figure 10 shows the results from the single bend tubes plotted against the muzzle angle. Noting that both positive and negative shapes were use in the simulations (Figure 4), the natural jump (jump from the gun's dynamics during launch using a straight tube) is not zero.

In fact, the natural jump can be seen in Figure 10. The CCF is a propellant temperature weighted average of COIs with the majority of the emphasis on the ambient propellant temperature. All the shots in this study were done using ambient propellant temperature conditions, therefore, the average of the shots should provide a reasonable estimate for the CCF of the system. From the left side of Figure 10, if the tubes used are the fleet, then the average would be around 0.75 mrad. This result differs some from the results of a straight gun tube. The reason for this is that the distribution of the single bend tubes is skewed downward. If the distribution of the gun tube shapes were symmetric, then the estimated CCF would agree with the straight gun tube's results.

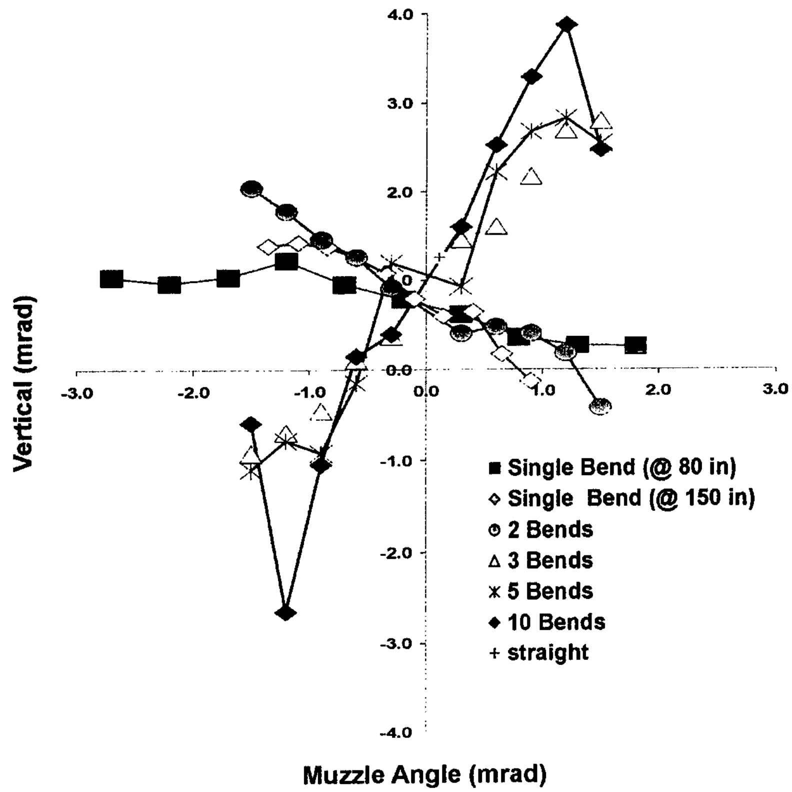

Figure 9. Vertical jump vs. magnitude of the muzzle angle.

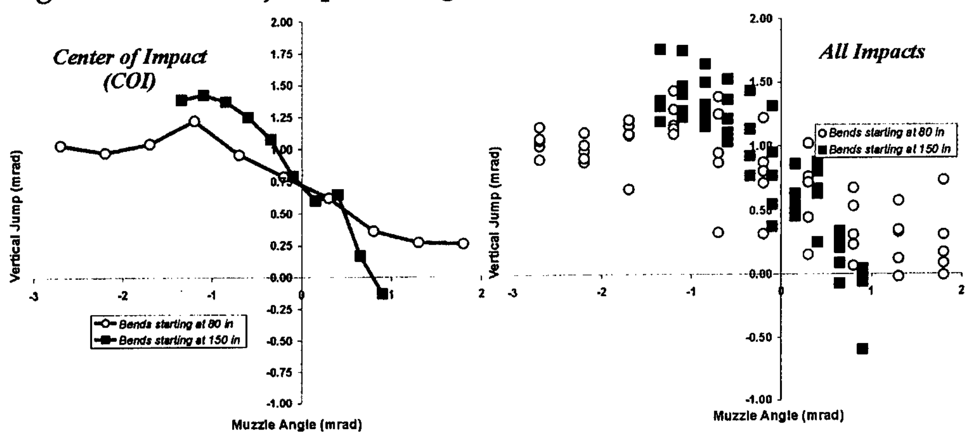

Figure 10. Sensitivity of location and magnitude of single tube bends.

To understand the implications of Figure 10, it is important to note that these tubes were bracketed into two groups, tubes with bend that start at 80 in (muzzle angle range between 1.8 mrad to -2.7 mrad), and tubes with bends starting at 150-in muzzle angle of 0.9 mrad to -1.35 mrad). The results show that the tubes with the smaller muzzle angle (bends further down the gun) cause greater jump variability (i.e., a large spread in jump even though the spread in the muzzle angle is small).

This again is attributed to the differences in transverse energy imparted to the projectile. For the case where the bend started at 150 in, the jump variability was larger because it has to navigate the angles at higher velocity than the tubes with bends starting at 80 in. Taking into account the previous lesson learned (i.e., in terms of the number of bends and muzzle angle magnitudes), this further strengthens the assertion that the tube, which imparts the smallest transverse interaction will show the least sensitivity to jump variability around this shape.

7. Conclusion

This report shows how to approach finding the optimal gun tube shape that produces the lowest jump variability. The approach uses theoretical gun tube shapes with bends that are within cannon manufacturing capabilities to show sources of jump error. The sensitivity of the jump error relative to shape and magnitude is also explored. The results show that the smallest jump variability (and least sensitivity) can be produced with a straight gun tube. Although these conclusions are drawn from analyzing only one round type, they are expected to be valid for all round types. In hindsight, recommending a straight centerline as the optimal tube shape may have been an obvious choice. This report provides, for the first time, at least a theoretical justification for such an assertion.

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